Title: Surface evolution of C-type asteroid 162173 Ryugu revealed from global mapping and touchdown operation of Hayabusa2

Short title: Geologic evolution of asteroid Ryugu.

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Abstract: The Hayabusa2 spacecraft touched down on the C-type near-Earth asteroid 162173 Ryugu for the first time on February 21, 2019. Based on the touchdown and global observations, we report on the nature of the stratigraphy of the surface materials as expressed in the color observations on Ryugu. The latitudinal variation of spectral slope suggests that exposure of Ryugu materials to space has led to their reddening by solar heating and/or space weathering. The dark fine grains lifted up by the thrusters immediately after touchdown may originate from the redder materials. The stratigraphic relationship between the craters and the redder materials suggests that surface reddening occurred over a short period of time about 8 million years ago. (117 words)

One Sentence Summary: Reddening of Ryugu's surface occurred in a short period of time, suggesting that Ryugu underwent an orbital excursion near the Sun (110 characters)

Main Text: (2576 words)

Hayabusa2, the first sample-return mission to a C-type asteroid (1), was launched on December 3, 2014 and arrived at the target near-Earth asteroid (NEA) 162173 Ryugu on June 27, 2019. It conducted global observations revealing a number of important properties of the asteroid, such as its top-shaped rubble pile nature (2,3), the presence of a small amount of hydrous minerals (4), a young surface age, and color properties consistent with partially dehydrated carbonaceous chondrites (5). Furthermore, more subtle properties, such as general spectral uniformity (4,5) and variation in spectral slope from b-band (0.48 μm) to x-band (0.86 μm) (hereafter, b-x slope) (2, 5, 6) are observed by the telescopic optical navigation camera (ONC-T) (Fig. 1A). The bluer materials are distributed at the equatorial ridge (Ryujin Dorsum) and in the polar regions, while the redder materials are widely spread over the mid-latitude regions (5). However, the nature of these spectral variations is still poorly understood.

On February 21, 2019, the Hayabusa2 spacecraft conducted successfully its first touchdown on Ryugu, obtaining the first sample from a C-type asteroid. During the touchdown operation, Hayabusa2 had an opportunity to take extremely high-resolution (~1 mm/pix) images of Ryugu's surface and to observe its response to the physical disturbances generated by the touchdown, including the sampling projectile collision and firing of the thruster gas jets. The series of touchdown observations revealed a number of important properties of Ryugu's surface regarding space weathering, grain size distribution, mixing of different materials especially with regard to their color properties, and stratigraphic relations among different materials. These properties are important for bridging the gap between meteoritic materials and asteroid surfaces. Furthermore, such characterization will help us to understand the geologic context of the samples captured in Hayabusa2's capsule chambers. We discuss the stratigraphy and geology of the touchdown site, the complex dynamic reactions of surface materials on Ryugu triggered by the physical contact of the Hayabsua2 spacecraft, and detailed textures and structures on pebbles and boulders captured in extremely high-resolution images during the touchdown operations. Based on these proximity observations and global observations, we infer the nature of the stratigraphy expressed in color and albedo properties of Ryugu's surface.

The touchdown site was selected based on both the established engineering safety criteria and the scientific merits for material sampling (2, 7). Ryugu's surface is comprised of two end-member compositional units; a spectrally redder and a spectrally bluer component. Sample materials that contain both components substantially increase our understanding of Ryugu's compositional elements. The spectral slope on Ryugu indicates regional variations in red/blue mixing ratios (Fig. 1A), but the presence of impact ejecta and evidence of mass wasting movement suggest Ryugu's surface has a well-mixed nature (5). Furthermore, the spectral differences among the different touchdown candidate sites are much smaller than the variation within each site (2). Thus, a touchdown to any of the candidate sites would have allowed us to obtain both redder and bluer components. However, because of the high boulder abundances (5, 8), the locations for safe landing were limited. (2). We chose L08-B, one of the lowest density boulder areas on Ryugu, as the primary landing site (2, 7) and deployed a target marker (TM) to facilitate navigation. However, based on the location where the TM settled and the detailed search for areas without boulders taller than 65 cm, which could reach Hayabusa2's reaction control system (RCS) during a touchdown, we finally chose to sample a smaller region in L08-E1 (Fig. 2A and S3).

During multiple low-altitude (~40 m) descent maneuvers near the L08 region, we conducted high-resolution spectral and morphologic observations. The touchdown spot is generally slightly bluer than the global average, but reddish spots are found within the L08-E1 region (Fig. 1E and 2C). These reddish spots tend to be darker than bluer areas, a trend that is observed globally (2, 5). The reddish spots are limited to the flat surface of several individual boulders, however a large part of boulder surfaces is blue (Fig. 2C). These observations suggest that the redder materials were created from bluer materials by some surface metamorphic processes such as space weathering, thermal metamorphism by solar heating, and/or simple pulverization. A large portion of the redder materials has been scraped off from the boulder surface by impact disruption and/or thermal fatigue. The fact that the bluer surfaces of boulders remain un-reddened implies that the timescale for surface reddening is currently sufficiently long compared with that of boulder resurfacing by impact disruption and/or thermal fatigue.

High-resolution (down to 1 mm/pix) images indicate that there are two morphologic types of sub-meter-sized boulders around the TD spot: dark ragged boulders and bright boulders with smooth surfaces (Fig. 2D). These types of boulders are also commonly observed in the ten-meter size range on Ryugu (5). The high-resolution images show a submeter-scale heterogeneity in surface reflectance of the bright boulders; edges of many boulders are brighter than the planar surfaces of the same boulders (yellow arrows in Fig. 2E), implying that the boulder surfaces were darkened by the exposure to space.

Hayabusa2 has a sampling mechanism similar to that of the original Hayabusa spacecraft, which catches ejecta generated by the impact of a 1-cm-diameter tantalum projectile shot at a speed of ~300 m/s during the first contact of Ryugu's surface with a 1-m long sampler horn extended from the bottom of the spacecraft (9, 10). The Hayabusa2 sampler horn also has a hold-up system on its edge to lift up ~1-cm-sized pebbles from the surface when the spacecraft starts to ascend due to upward acceleration (11).

The combination of the impact of the projectile shot from the sampler system and the RCS thrust during the touchdown produced a large amount of debris from Ryugu's surface (Fig. 2 and Movie S1) (6). The motion picture obtained by the nadir-viewing wide-angle optical navigation camera (ONC-W1) indicates that large boulders (up to 1 m in the longest dimension) moved horizontally by >5 m. However, the majority of debris disturbed upon the touchdown was small pebbles and fine grains whose diameters are less than the pixel size (1 to a few mm) as observed within the highest resolution W1 images (6). The observed high mobility of regolith during the touchdown indicates that the inter-boulder/inter-pebble cohesion may be very weak. The high mobility is consistent with observations of an extremely low number density of small craters, mass wasting on crater walls, and the crater formation by the small carry-on impactor (SCI) in the gravity-dominated regime (5, 12–14).

Immediately after the RSC thrust upon touchdown, the entire field-of-view of ONC-W1 was darkened uniformly, while a dark ragged boulder nicknamed "turtle rock" simultaneously became as bright as surrounding brighter boulders (Fig. 2D) (6). These observations suggest that dark fine grains were originally present on the surface and inside the pores of darker and redder boulders. These dark, fine grains were lifted up by the RSC thrusting, although the fine grains have not been observed by the Mobile Asteroid Surface Scout (MASCOT) lander (15). The sampling process formed a cloud of dark fine grains radiating from the touchdown site that extended to ~10-m in diameter, centered on the touchdown site (Fig. 2, G and H). The total mass of the fine-grained cloud is estimated to be > 3 kg (6). The pre-touchdown color of this region was slightly bluer than the surrounding region but it became redder after the deposition of the lofted dark fine grains (Figs. 2G and S5). However, few changes in the OH band depth were detected by the Near Infrared Spectrometer (NIRS3) before versus after the touchdown (Fig. S6). These observations suggest that the dark fine grains originated from the redder materials originally coating the boulder surfaces.

Because of the great variety of dynamic responses and fine textures in Ryugu's surface materials observed during the touchdown operation, not all these properties are yet fully understood. However, the relations among the different phenomena allow us to infer the causes of the color changes. Comparisons between touchdown observations and global observations are useful for also understanding the source of these color changes. In particular, the relation between redder/darker and bluer/brighter components is important. More specifically, the general spectral slope is the most prominent factor in defining the color variation observed on Ryugu (5) (Fig. 1A). The above discussion based on the touchdown observations shows that this variation is likely connected with the presence, or lack thereof, of dark reddish fine grains.

In addition to the latitudinal variation in b-x slope (Fig. 1A), it was found that the spatial variation in b-x slope also correlates with the crater distribution. Fresh and stratigraphically later (younger) craters larger than ~20 m in diameter have spectrally bluer interiors compared to the surrounding materials (Fig. 1, B and C). This implies that the redder materials were covering the bluer materials and the underlying bluer materials were exposed by the crater formation, consistent with the stratigraphic relationship between the redder and bluer materials inferred from the global distribution of b-x slope. On the other hand, stratigraphically earlier (older) craters tend to have redder interiors, and the color of the crater interiors has no difference with that of surrounding materials (Fig. 1, B and C). We investigated the contrasts in spectral slopes between crater interior surfaces and surrounding areas, defined as the area within a crater radius from the crater rim. The obtained histogram of the contrast in b-x spectral slope shows a bimodal distribution (Fig. 3), indicating that craters on Ryugu can be divided into two groups: red craters whose interior has b-x slope similar to that of their surroundings and blue craters whose interior is bluer than their surroundings.

A probable explanation of the latitudinal variation in b-x slope is that while the exposure of Ryugu's materials to space has led to their reddening, mass wasting from the equator and polar regions (topographic highs) to the mid-latitude regions (topographic lows) at the current spin state of Ryugu exposed fresh bluer subsurface materials (2, 5). The polar regions exhibit bluer spectra than the equatorial ridge (Fig. S1), suggesting the reddening process by thermal metamorphism and/or space weathering by solar radiation (Ryugu's obliquity is 171.6˚ (2)). The color variation of crater interiors can be explained by their stratigraphic relation; the craters with redder interiors were formed before the surface reddening and their interiors were discolored by the surface reddening, while the blue craters were formed after the surface reddening and the underlying bluer materials were exposed by the blue-crater-forming impacts. The bimodal distribution of the contrast in b-x spectral slope (Fig. 3) suggests that the surface reddening has not been active throughout Ryugu's history and occurred within a short time interval after the formation of redder craters and before the formation of bluer craters. These results are consistent with the interpretation that the timescale for surface reddening is currently sufficiently long compared with that of boulder resurfacing based on the color distribution of boulder surface revealed by high-resolution spectral observations (Fig. 2C).

Based on collision frequency models for the asteroid main belt (16, 17), the observed size–frequency distribution of red craters larger than 100 m in diameter (Fig. 3D) leads us to estimate the time from the top-shape formation of Ryugu to the surface reddening to be 8.5 Ma (based on gravity-dominated crater scaling (14)). Because the observed number density of blue craters is ~1/30 of that of red craters, the model age of the reddening event is estimated to be about 0.3 Ma for the main-belt impact frequency. In contrast, if the reddening occurred after the orbital transition to its current near-Earth orbit, the reddening age would be about 8 Ma because of the much lower collision frequency for NEA orbits (16, 17). The NEA model age is younger than the typical dynamical lifetime of NEAs (~10 Ma) (18) and the median lifetime of Ryugu (~40 Ma) (19), compatible with the interpretation that the reddening of Ryugu's surface was caused after the orbital transition from the main belt to its current near Earth orbit.

The deficit of craters smaller than 100 m in diameter suggests that crater erasure processes, such as seismic shaking, were active on Ryugu's surface and therefore existing small craters must have formed geologically recently (5). However, smaller craters (<10 m in diameter) do not always exhibit bluer interior despite their youth; some small craters exhibit a redder, not bluer, interior than the surroundings materials (Fig 1D and 1E). More detailed observations show a streaked pattern of redder materials such as ejecta deposits (Fig. 1C and Fig. S2B). In addition, redder materials that are fractured by collision with a boulder are found (Fig. S2F). Thus, redder materials may have been disrupted and redistributed by the impacts, thermal fatigue, and regolith migration, which may have resulted in the formation of a mixed layer of redder and bluer materials after the surface reddening (Fig. 4). This interpretation is supported by the distribution of redder materials on boulder surfaces and the existence of dark reddish fine grains observed in the touchdown operation. The thickness of the mixing layer is estimated to be a few meters from the minimum crater size (~10 m in diameter) penetrating to the underlying blue material layer. The existence of a-few-tens-of-meters-long ejecta consisting of redder materials (Fig. S2F) means that the redder material layer had originally a thickness of tens of centimeters to meters at minimum. Therefore, the solar heating is a more likely process than space weathering to be the source of the reddening of Ryugu's surface since space weathering typically affects only a thin layer of about 100 nm deep from the particle rim, while the diurnal and annual thermal skin depths are <~ 10 cm and ~1.5 m, respectively (20, 21).

The evidence that surface reddening occurred within a short period of time suggests that Ryugu underwent a temporary orbital excursion near the Sun, which resulted in surface heating by the Sun. Such solar heating is consistent with the apparent deficiency in 0.7-µm bearing C-type asteroids in the NEA population (22). The effect of solar heating may also explain the difference in global color variations between similar C-type asteroids, Ryugu and Bennu, the target of NASA's OSIRIS-REx mission (23–29). The apparent lack of latitudinal variation in the spectral slope on Bennu (24, 26) may suggest that Bennu has not undergone a similar orbital excursion near Sun. However, such solar heating on Ryugu during its orbital excursion cannot account for the low amount of hydrous minerals constrained from both the shallow 2.7-µm absorption band (4) and the lack of a strong 0.7-µm absorption (5). This is because the bluish/brighter areas on Ryugu, which did not experience the intense solar heating (e.g., equatorial ridge and polar regions), also display a weak 2.7-µm absorption (4).

The spatial distribution in the b-x slope within the touchdown site also has important implications for the samples obtained in the first touchdown by Hayabusa2. Because the L08-E1 site is one of the bluest areas compared with the global average, samples obtained from this site likely contain bluish/brighter components, which are likely free from the recent intense solar heating. Furthermore, the large local variations in the spectral slope and albedo within the sampling site suggest that both bluer and redder components were likely collected. Detailed laboratory analyses of these returned components of Ryugu will reveal the nature of mineralogical and geochemical characteristics of these components and their spectral manifestations, and ultimately provide insight into the multiple stages of Ryugu's material evolution.

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Supplementary Materials:

Supplementary Text SM1 to SM7
Figs. S1 to S11
Tables S1
Movie S1
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